ROGER C. REED

The SUPERALLOYS

Fundamentals and Applications

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The Superalloys

Superalloys are unique high temperature materials used in gas turbine engines, which display excellent resistance to mechanical and chemical degradation. This book presents the underlying metallurgical principles which have guided their development and practical aspects of component design and fabrication from an engineering standpoint. The topics of alloy design, process development, component engineering, lifetime estimation and materials behaviour are described, with emphasis on critical components such as turbine blades and discs.

The first introductory text on this class of materials, it will provide a strong grounding for those studying physical metallurgy at the advanced level, as well as practising engineers. Included at the end of each chapter are exercises designed to test the reader's understanding of the underlying principles presented. Additional resources for this title are available at www.cambridge.org/9780521859042.

ROGER C. REED is Professor and Chair in Materials Science and Engineering at Imperial College London. From 1994 to 2002, he was Assistant Director of Research in the Rolls-Royce University Technology Centre at the University of Cambridge. From 2002 to 2005, he held a Canada Research Chair in the Department of Materials Engineering at the University of British Columbia, Vancouver. He is widely known in the gas turbine community for his work on the physical metallurgy of the superalloys, and has taught extensively in this field.

But if I were to say, my fellow citizens, that we shall send a rocket to the moon, 240 000 miles away from the control station in Houston, a giant rocket more than three hundred feet tall, the length of this football field, made of new metal alloys, some of which have not yet been invented, capable of standing heat and stresses several times more than have ever been experienced, fitted together with a precision better than the finest watch, carrying all the equipment needed for propulsion, guidance, control, communications, food and survival, on an untried mission, to an unknown celestial body, and then return it safely to Earth, re-entering the atmosphere at speeds of over 25 000 miles per hour, causing heat about half that of the temperature of the sun, almost as hot as it is here today, and do all this, and do it right, and do it first before this decade is out, then we must be bold . . .

From John F. Kennedy's speech at Rice University, Houston, Texas, 12 September 1962

Foreword

I am grateful to Cambridge University Press for allowing me to make some comments about Roger Reed's new textbook *The Superalloys: Fundamentals and Applications*. Nickel-based superalloys represent a very important class of engineering material, finding widespread application for example in critical components within the gas turbine engines used for jet propulsion and electricity generation. This is due to their superior mechanical properties that are maintained to elevated temperatures. Indeed, new classes of superalloy are continually being sought by gas turbine manufacturers around for the world for applications in the hottest parts of the engine. This is because higher temperatures result in improvements to the efficiency of the engine and therefore lower fuel burn. Engine performance is a major factor in any power plant competition, which helps to explain why all the engine manufacturers spend so much money developing future generations of superalloys.

The author has provided us with a textbook covering both the fundamentals and applications of superalloy technology. This is a significant and unique achievement, especially given the broad range of subject matter dealt with. In Chapter 1, the requirement for materials capable of operating at elevated temperatures is introduced along with the historical development of the nickel-based superalloys and their emergence as materials for high-temperature applications. Chapter 2 concerns the physical metallurgy of the superalloys, with an emphasis on the details which distinguish them from other classes of engineering alloys, for example the gamma prime strengthening phase, the role of defects such as the anti-phase boundary, the unique particle-strengthening mechanisms, the anomalous yield effect and the creep deformation behaviour. Chapters 3 and 4 deal with superalloy technology as applied to two major gas turbine components of critical importance: the turbine blade and discs. Of note is the balanced coverage given to the processing, alloy design and microstructure/property relationships relevant to superalloys used for these distinct applications. Chapter 5 deals with surface coatings technologies, which are becoming increasingly critical as operating temperatures continue to rise. In Chapter 6, projections are made about the future of superalloy technology.

In view of the author's exemplary treatment of the subject, this tectbook deserves to become the definitive textbook in the field for the foreseeable future. I have found myself referring to it on many occasions already! It is recommended to all those with an interest in the field of high-temperature materials, particularly those involved with gas turbine technology or those embarking on a higher degree in the subject. Also, since the superalloys represent a considerable success story in the field of materials science and engineering, it is recommended for use within the materials-related curricula at universities.

Dr Mike Hicks
Chief Technologist – Materials
Rolls-Royce plc

Preface

Based upon nickel, but containing significant amounts of at least ten other elements including chromium and aluminium, the superalloys are high-temperature materials which display excellent resistance to mechanical and chemical degradation at temperatures close to their melting points. Since they first emerged in the 1950s, these alloys have had a unique impact. Consider the aeroengines which power the modern civil aircraft. The superalloys are employed in the very hottest sections of the turbines, under the heaviest of loads, with the utmost importance placed on assuring the integrity of the components fabricated from them. Indeed, the development of the superalloys has been intrinsically linked to the history of the jet engine for which they were designed; quite simply, a modern jet aeroplane could not fly without them. Further improvements in temperature capability are now being actively sought, for example for the engines to power the two-decked Airbus A380 and the Boeing 787 Dreamliner. Superalloys are being employed increasingly in the land-based turbine systems used for generating electricity, since fuel economy is improved and carbon emissions are reduced by the higher operating conditions so afforded. But new developments in superalloy metallurgy are required for the next generation of ultra-efficient power generation systems. Over the next 25 years, the world's installed power generation capacity is expected to double, due to the rapidly growing economies and populations of the developing countries, and because most of the current plant in the developed countries will need to be replaced. Thus the superalloys have never been more important to the world's prosperity.

The remarkable performance of today's superalloys is not merely fortuitous. Numerous researchers and technologists have worked to develop the basic understanding of their physical behaviour and the more practical aspects required to put these alloys to best use. With this book, the reader is presented with an introduction to the metallurgical principles which have guided their development. It turns out that the topics of alloy design, process development, component engineering, lifetime estimation and materials behaviour are very closely inter-related. The book is aimed at those pursuing degrees in Materials Science and Engineering, but those studying Mechanical Engineering, Aerospace Engineering, Physics and Chemistry will also find it useful. It has been developed with two audiences in mind: first, final-year undergraduate students taking an elective course in high-temperature materials technology, and, secondly, students embarking on a higher degree in this field who seek an introduction to the subject. Included at the end of the first five chapters are questions designed to test the reader. Many of these require numerical working using a calculator, spreadsheet or computer programming tool. Most of these exercises have been tested on students at Imperial College, the University of Cambridge and the University of British Columbia, where I have held teaching positions. I would like to receive comments from those who have attempted the problems – I will attempt to answer all queries as promptly as I can. My email address can be found at www.cambridge.org/9780521859042.

In preparing the book, the reader should be aware that it has been necessary to be selective about the content included in it. I have included sufficient material to satisfy the requirements of a one-course semester – about 30 hour-long periods, some of which should be used for classwork, problem sets and design exercises. In my own teaching I have used the book's contents to emphasise the relationships between the structure/composition of these materials, their mechanical/chemical behaviour, the processing of them and the design of the components which have provided the technological impetus for their development. Thus, a proper balance between these different topics has been sought; the need for this makes the superalloys an excellent case study in the field of materials.

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Contents

1 Introduction

1.1 Background: materials for high-temperature applications

1.1.1 Characteristics of high-temperature materials

Certain classes of material possess a remarkable ability to maintain their properties at elevated temperatures. These are the *high-temperature materials*. Their uses are many and varied, but good examples include the components for turbines, rockets and heat exchangers. For these applications, the performance characteristics are limited by the operating conditions which can be tolerated by the materials used. For example, the thrust and fuel economy displayed by the modern aeroengine is strongly dependent upon, and limited by, the high-temperature strength of the nickel-based superalloys used for its hottest sections.

What are the desirable characteristics of a high-temperature material? The first is *an ability to withstand loading at an operating temperature close to its melting point*. If the operating temperature is denoted T_{oper} and the melting point T_m, a criterion based upon the homologous temperature τ defined as T_{oper}/T_m is sensible; this should be greater than about 0.6. Thus, a superalloy operating at 1000 °C in the vicinity of the melting temperature of nickel, 1455 °C, working at a τ of $(1000 + 273)/(1455 + 273) \sim 0.75$, is classified as a high-temperature material. But so is ice moving in a glacier field at −10 °C, since τ is $263/273 \sim 0.96$, although its temperature is substantially lower. A second characteristic is *a substantial resistance to mechanical degradation over extended periods of time*. For high-temperature applications, a time-dependent, inelastic and irrecoverable deformation known as *creep* must be considered – due to the promotion of thermally activated processes at high τ. Thus, as time increases, creep strain, ϵ_{creep}, is accumulated; for most applications, materials with low rates of creep accumulation, $\dot{\epsilon}_{creep}$, are desirable. In common with other structural materials, the *static* properties of yield stress, ultimate tensile strength and fracture toughness are also important – and these must be maintained over time. A final characteristic is *tolerance of severe operating environments*. For example, the hot gases generated in a coal-fired electricity-generating turbine are highly corrosive due to the high sulphur levels in the charge. Kerosene used for aeroengine fuel tends to be cleaner, but corrosion due to impurities such as potassium salts and the ingestion of sea-water can occur during operation. In these cases, the high operating temperatures enhance the possibility of oxidation. Under such conditions, any surface degradation reduces component life.

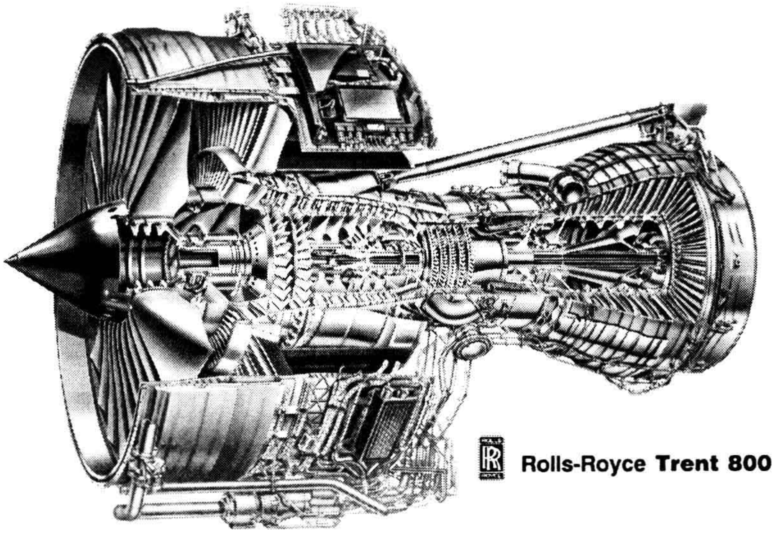

Fig. 1.1. Artist's impression of the turbomachinery in Rolls-Royce's Trent 800 engine, which powers the Boeing 777 aircraft. (Courtesy of Rolls-Royce.)

1.1.2 The superalloys as high-temperature materials

When significant resistance to loading under static, fatigue and creep conditions is required, the nickel-base superalloys [1–3] have emerged as the materials of choice for high-temperature applications. This is particularly true when operating temperatures are beyond about 800 °C. This is the case for gas turbines used for jet propulsion, for example, the 100 000 lb thrust engines used for the Rolls-Royce Trent 800 and General Electric GE90 which power the Boeing 777 [4] (see Figure 1.1), but also the smaller 1000 lb engines used for helicopter applications. Gas turbines are used also for electricity generation, for example, the 250 MW gas-fired industrial plant which can generate enough power to satisfy a large city of a million people (see Figure 1.2), or the smaller 3 MW gas-fired generators suitable for back-up facilities [5]. When weight is a consideration, titanium alloys are used, but their very poor oxidation resistance restricts their application to temperatures below about 700 °C [6]. For some electricity-generating power plant applications which rely upon superheated steam at 565 °C, high-strength creep-resistant ferritic steels are preferred on account of their lower cost. However, the latest generation of ultra-supercritical steam-generating coal-fired power stations requires boiler tubing that can last up to 200 000 hours at 750 °C and 100 MPa – new types of superalloy are being developed for these applications [7], since ferritic steels cannot be designed to meet these property requirements. Generally speaking, ceramics such as silicon carbide and nitride are not used for these applications, despite their excellent oxidation and creep resistance, due to their poor toughness and ductility. Zirconia-based ceramics do, however, find applications in thermal barrier coatings which are used in association with the superalloys for high-temperature applications.

Since the technological development of the superalloys is linked inextricably to the gas turbine engine, it is instructive to consider the functions of its various components [8].

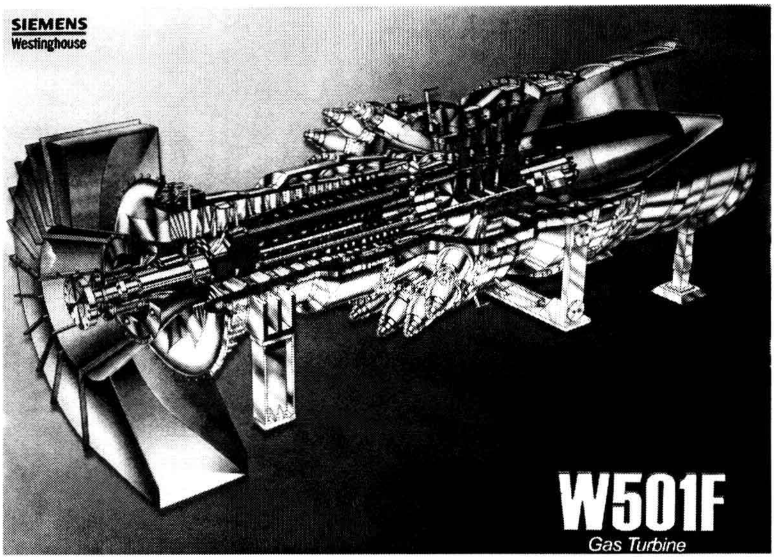

Fig. 1.2. Artist's impression of the turbomachinery in Siemens Westinghouse's W501F gas turbine engine, used for electricity generation. (Courtesy of Siemens Westinghouse.)

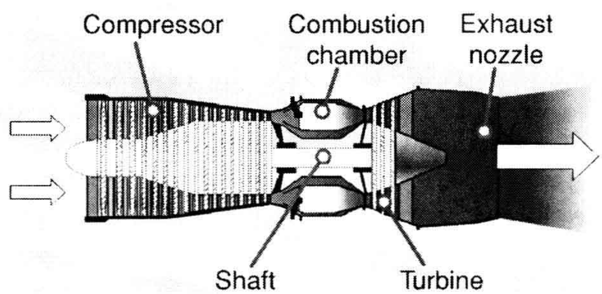

Fig. 1.3. Diagram illustrating the basic features of a very basic gas turbine engine: the turbojet. (Courtesy of Rolls-Royce.)

Consider the turbojet engine, Figure 1.3. The role of the *compressor*, consisting of compressor blades and discs, is to squeeze the incoming air, thus increasing its pressure. The compressed air enters the *combustor*, where it is mixed with fuel and ignited. The hot gases are allowed to expand through a *turbine*, which extracts the mechanical work required to drive the compressor; this necessitates a *shaft*, which transmits the torque required for this to happen. In the case of the turbojet, thrust arises from the momentum change associated with the incoming air being accelerated and its emergence as exhaust gas at a significantly higher velocity. Variants of this basic design are possible. In a turbofan engine, an additional low-pressure compressor, or *fan*, is added to the front of the engine. Although this necessitates an additional shaft and an associated turbine to drive it, the weight penalty associated with the extra turbomachinery is offset by the greater fuel economy – this arises from the

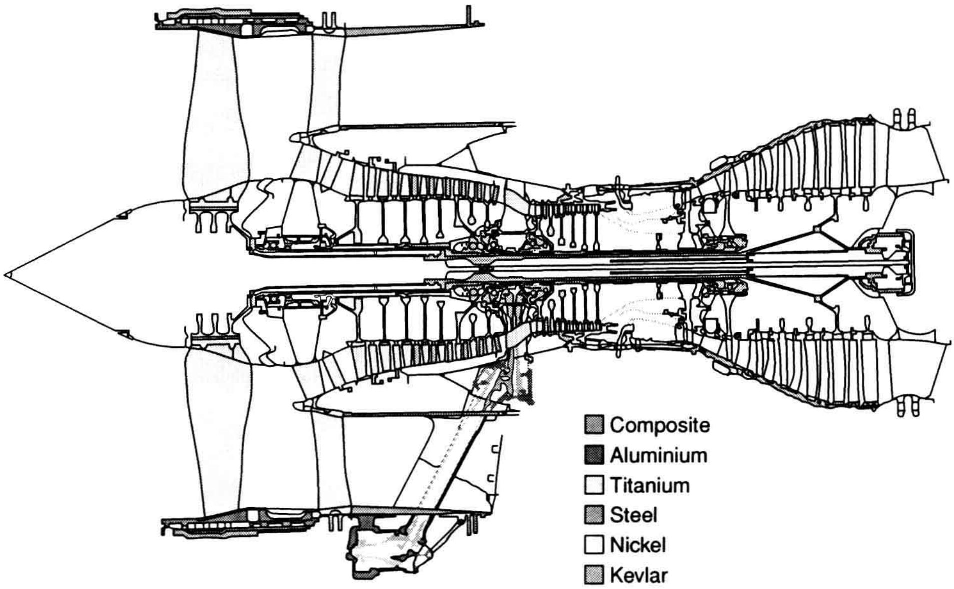

Fig. 1.4. Illustration of material usage in the Trent 800 engine. Note the extensive use of nickel-based superalloys in the combustor and turbine sections (see the back cover for a colour version of this figure). (Courtesy of Rolls-Royce.)

thrust provided from the air, which *bypasses* the turbines. Figure 1.4 illustrates the different materials used in the various parts of the Trent 800 aeroengine. One sees that titanium alloys are chosen for the fan and compressor sections, on account of their low density, good specific strength and fatigue resistance. However, in the combustor and turbine arrangements, the nickel-based superalloys are used almost exclusively. Superalloys are used also in the final (high-pressure) stages of the compressor.

When designing a gas turbine engine, great emphasis is placed on the choice of the *turbine entry temperature* (TET): the temperature of the hot gases entering the turbine arrangement [9]. There, the temperature falls as mechanical work is extracted from the gas stream; therefore the conditions at turbine entry can be considered to be the most demanding on the turbomachinery and the nickel-based superalloys from which are they made. As will be seen in Section 1.2, the performance of the engine is greatly improved if the TET can be raised – and over the 50 years since their conception, this has provided the incentive and technological impetus to enhance the temperature capability of the superalloys, and to improve their processing and the design of components fabricated from them. The success of these enterprises can be judged from the way in which the TET of the large civil aeroengine has increased since Whittle's first engine of 1940 (Figure 1.5); a 700 °C improvement in a 60-year period has been achieved [10]. Of course, the TET varies greatly during a typical flight cycle (see Figure 1.6), being largest during the take-off and climb to cruising altitude. Turbines for power-generating applications experience fewer start-up/power-down cycles but very much longer periods of operation, during which the TET tends to be rather constant.